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Size and Location of the Human Temporomandibular Joint

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ABSTRACT The literature abounds with conflicting data on various morphometric aspects of the temporomandibular joint (TMJ). The purpose of this study was to observe the effects of sex, ethnic group, and edentulism on TMJ osseous morphology and to define possible factors which might influence variation in this structure. TMJs and related craniofacial structures were measured directly on 229 dry skulls and matching mandibles. Analysis of variance, principal component analysis, and cluster analysis were performed. Our results indicate that 1) the anteroposterior-related TMJ dimensions are independent of sex, ethnic group, and edentulism; 2) the transverse TMJ dimension is related to cranial breadth measures; and 3) the projected distance, along a midsagittal plane, between the TMJ and foramen magnum is independent of sex, ethnicity, and edentulism. It is our assertion that the TMJ must not be considered as a single morphological structure but rather viewed as a functional unit with component parts which are subordinate to completely different sets of influences. © 1996 Wiley-Liss, Inc.

The skull is a source of taxonomic information. To date, measurements have generally been considered of value if they possess discriminate power regardless of whether their variation has been taxonomic, functional, or genetic in origin. The present study of temporomandibular joint (TMJ) osseous morphology will attempt to shift the focus from variation to stability.

Studies of the osseous morphology of the human TMJ (i.e., the mandibular condyle, mandibular fossa, and articular eminence) have been manifold in anthropological literature. Factors such as sex, ethnic origin, and degree of edentulism have been shown to be associated with significant variation in several aspects of the craniofacial skeleton, yet their effects on the TMJ have been disputed. The following is an overview of the major contradictory findings which have been documented in this regard.

INTRINSIC FACTORS (SEX, ETHNIC ORIGIN)

The size and shape of the mandibular condyle vary little with either sex or ethnic origin. Solberg et al. (1985) found condylar breadth to be the only significant size or shape difference between males and females. Others (Oberg et al., 1971) found no significant metric or nonmetric differences between the condyles of males and females or reported some differences between the sexes in the distribution of condylar form but no differences according to ethnic group (Yale et al., 1966).

Regarding the mandibular fossa, Demirci-

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oglu (1961) found significantly deeper fossae in males than in females and moderately significant differences based on ethnic origin. A decrease in mandibular fossa dimensions over a 5,000 year period due to changes in subsistence mode have also been observed (Hinton and Carlson, 1979).

Solberg et al. (1985) found fossa breadth and one anteroposterior measurement to be significantly greater in male than in female TMJs. Other dimensions, however, did not manifest significant differences. These included no significant differences in fossa size or shape (Oberg et al., 1971), no clear sex differences in articular tubercle height (Ingervall, 1974), and no difference in mandibular fossa depth between the sexes (Nevakari, 1960). Yet Lindblom (1960) found the length of the anterior wall of the mandibular fossa in males and females to differ significantly on TMJ radiographs.

EXTRINSIC FACTOR: EDENTULISM

Most authors agree that edentulism produces some degree of stress-related changes in TMJ morphology. Hinton and Carlson (1979) suggested an interdependence between stress on the dentition and TMJ morphology since, aside from the joint, maxillary and mandibular dentition are the only other contact (albeit indirect) between the mandible and cranium. Few studies have evaluated comprehensively the effects of edentulism on the osseous morphology of the TMJ, but changes in the dentition have been associated with the remodeling of mandibular condylar contours (Yale et al., 1966). Condylar remodeling could be a structural response to functionally induced changes in mechanical stress on the bone (Mongini, 1972). A relationship between condylar remodeling and lack of molar support has also been suggested (Hansson et al., 1979), and autopsy studies have found associations between tooth loss and changes in TMJ osseous morphology (Kopp and Carlsson, 1988).

Attrition and edentulism significantly reduce the slope on the posterior aspect of the articular eminence (Granados, 1979). Edentulism yields shallower fossae and more gradual eminence slopes in comparison to a control group with good dentition (Lawther, 1956). No significant correlation was observed between dental wear and fossa depth (Demircioglu, 1961), and yet molar loss and the dental function of a given population seem to influence fossa morphology (Hinton, 1981).

In sum, previous studies disagree on the factors associated with TMJ osseous morphology. It is generally accepted that some aspects of the human skull vary in accordance with intrinsic factors such as sex and ethnic group as well as functional factors such as edentulism. The question, however, remains whether these differences are expressed in the TMJ or whether the TMJ possesses intrinsic constraints which afford it a degree of independence from the craniofacial skeleton.

MATERIALS AND METHODS

Sample

The Hamann-Todd Osteological Collection housed at the Cleveland Museum of Natural History was used for the present study. The material consisted of a total of 229 skulls with mandibles (66 Euro-American (E-A) fully dentate male crania, 60 African-American (A-A) fully dentate male crania, 52 E-A fully dentate female crania, and 51 E-A edentulous male crania). The age distribution was as follows: 39 (20–29 years); 52 (30–39 years); 44 (40–49 years); 36 (50–59 years); 37 (60+ years). Twenty-one other crania of indeterminate age were excluded from the sample.

Measurements

With the exception of bizygomatic breadth and fossa depth, the metric cranial measurements were recorded from notations made with a craniograph (Fig. 1). The standard cranial measurements were made in accordance with Bass (1987). Fossa breadth in the transverse dimension (FTR) was measured between the lowest point on the articular tubercle and the temporal spine (junction of the sphenotemporal suture and the squamotympanic fissure). Anteroposterior fossa dimensions (FAP) were measured from the postglenoid tubercle to the midpoint of a line connecting the lowest point on the articular tubercle and the temporal spine (Fig. 1).

The projected angle (FANPR) is the angle

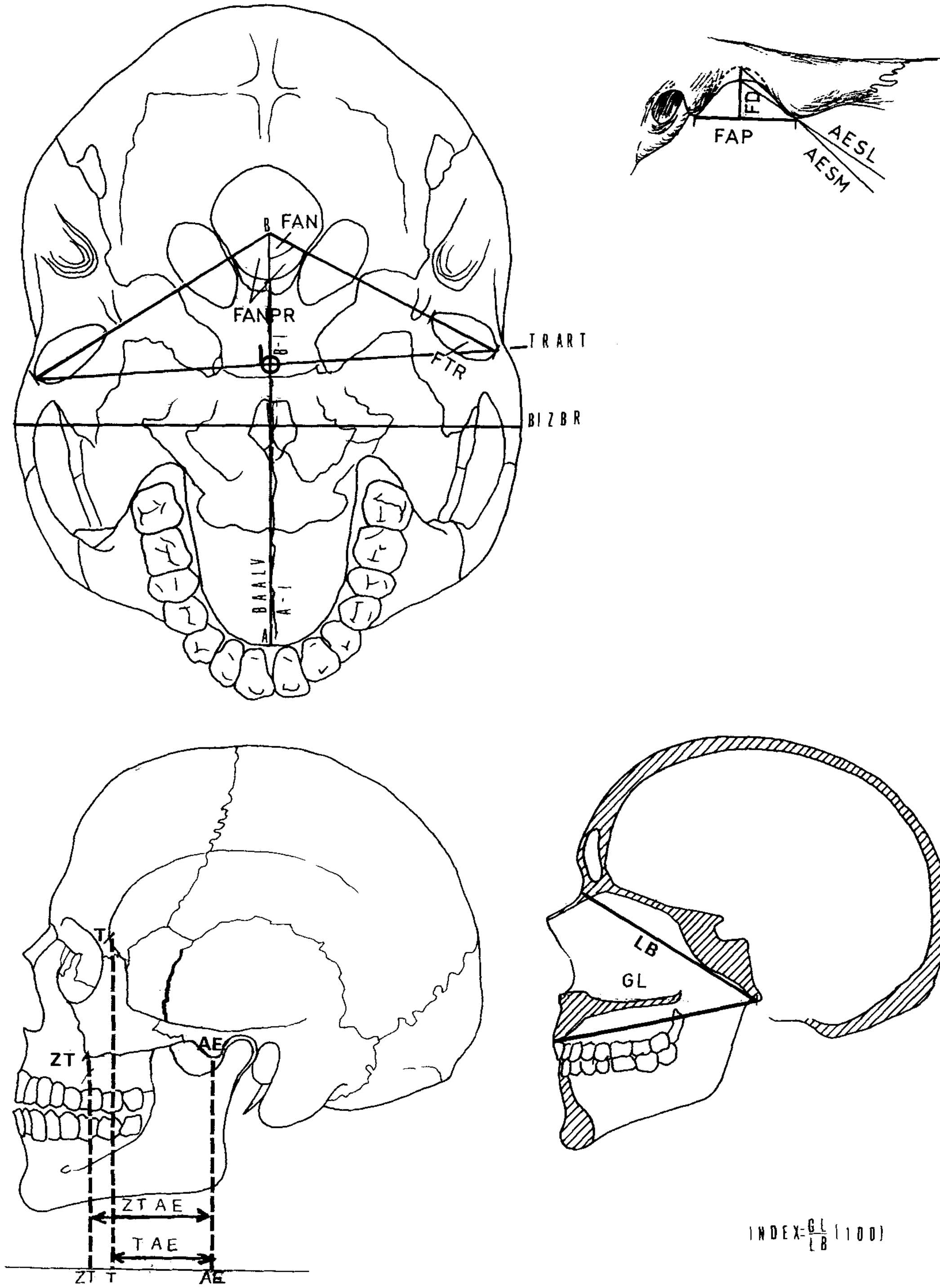

Fig. 1. Drawing demonstrating the main measurements taken in the present study. BIZBR, bizygomatic breadth; TRART, transarticular; BAALV, basion-alveolare; A-I, alveolare to intersection BAALV-TRART; B-I, basion to intersection BAALV-TRART; FAP, fossa dimensions, anterior to posterior; FTR, fossa dimensions, medial to lateral; FD, fossa depth; FANPR, fossa angle, projected; AESM, articular eminence slope, medial aspect; AESL, articular eminence slope, lateral aspect; GL, alveolare-basion length; LB, nasion-basion length; INDEX, gnathic index; ZTAE, zygomatic tubercle (ZT)-articular tubercle (AE) length; TAE, frontotemporale (T), articular tubercle (AE) length. (Suffixes or additional R = right; suffixes or additional L = left).

TABLE 1. Craniofacial measurements, male vs. female, Euro-Americans only, complete dentition

	Males			Females			Difference	
Trait[1]	N	Mean	SD	N	Mean	SD	F ratio	*P*
BIZBR	63	131.7	5.8	50	122.1	4.9	87.79	.0000*
FAPR	66	11.7	1.4	50	11.3	1.0	2.76	.0997
FAPL	66	11.8	1.4	52	11.6	1.3	.86	.3563
FTRR	66	25.7	2.1	52	23.7	2.0	26.77	.0000*
FTRL	66	25.6	2.2	52	23.9	1.9	19.75	.0000*
FDR	65	8.9	1.2	52	8.5	1.4	2.29	.1329
FDL	66	9.0	1.3	52	8.7	1.4	1.35	.2471
FANR	63	24.5	5.2	49	23.5	4.9	1.12	.2917
FANL	66	24.9	5.1	52	23.6	5.5	1.95	.1652
FANPR	63	131.1	8.2	52	133.4	10.4	1.89	.1724
AESRM	66	38.1	7.6	52	38.6	8.5	.10	.7571
AESRL	64	31.4	7.6	52	30.6	6.9	.38	.5396
AESLM	66	35.8	7.7	52	32.5	7.3	5.58	.0198
AESLL	66	29.8	7.5	52	28.4	6.5	1.17	.2816
GL	63	94.5	5.4	42	90.0	5.5	16.60	.0001*
LB	61	99.5	3.1	42	92.9	4.3	79.70	.0000*
INDEX	63	94.4%	4.7%	39	97.3%	4.0%	10.54	.0016*
ZTAER	66	45.0	4.8	49	40.5	2.8	34.00	.0000*
ZTAEL	66	44.7	4.8	51	40.5	3.7	26.74	.0000*
TAER	61	49.5	3.2	52	45.0	3.8	47.45	.0000*
TAEL	66	49.9	4.0	52	45.3	3.5	42.18	.0000*

[1] BIZBR, bizygomatic breadth; FAP, fossa dimensions, anterior to posterior; FTR, fossa dimensions, medial to lateral; FD, fossa depth; FAN, fossa angle; FANPR, fossa angle, projected; AESM, articular eminence slope, medial aspect; AESL, articular eminence slope, lateral aspect; GL, alveolare-basion length; LB, nasion-basion length; INDEX, gnathic index; ZTAE, zygomatic tubercle–articular tubercle length; TAE, frontotemporale, articular tubercle. In all tables, suffixes or additional R = right; suffixes or additional L = left; suffixes or additional A = anterior; suffixes or additional P = posterior.
* Significance = $P < 0.002$ (using Bonferoni criterion).

created at the intersection of the long axes of the two TMJs (Fig. 1). The anterior extent of the masseter and temporalis muscles was measured as described by Rak (1983), with projections from the zygomatic tubercle (TAE) and frontotemporale (ZTAE) to the articular tubercle (for masseter and temporalis respectively) (Fig. 1). Gnathic index was determined as described by DeVillers (1968) (100 nasion-basion length/alveolare-basion length).

Articular eminence slope was measured in two positions in accordance with Ichikawa and Laskin (1989). The lateral slope measurement (AESL) was made on a line extending from the lowest point on the articular tubercle to the highest point along the lateral curvature of the mandibular fossa. The medial slope measurement (AESM) was taken between two points 1 cm medial to the lateral points, one in the fossa and the other on the crest of the articular eminence (Fig. 1).

Fossa depth (FD) (Fig. 1) was measured by creating casts in Coecal dental stone mixed with water (Coe Laboratories, Chicago, Il). A standard stick pin was placed between the lowest point on the articular tubercle and the temporal spine before the Coecal dried. Using a sliding caliper we measured the depth from the line created by the pin to the deepest point on the fossa cast.

The relative position of the mandibular fossa vis-à-vis the basicranium was measured as follows: an A-P mid-sagittal line was drawn between the alveolare and basion (BAALV) (Fig. 1), and a line perpendicular to it was drawn, joining the most inferolateral points on the articular tubercles (Transarticular), [TRART] (Fig. 1). Two distances were defined: from basion to the point of intersection (B-1) and from the intersection point to alveolare (A-I) (Fig. 1).

Standard mandibular measurements were made as described by Martin and Saller (1957) or DeVillers (1968). Condylar breadth (COSTR) was measured bilaterally as the distance between medial and lateral condylar poles. Anteroposterior condylar measurements (COSAP) were made at the level of the joint capsular attachments halfway between the two condylar poles. Projected condylar angle (COPRAM), the angle created when rays projecting from bilateral condylar

TABLE 2. Mandibular measurements, male vs. female, Euro-American only, complete dentition

	Males			Females			Difference	
Trait[1]	N	Mean	SD	N	Mean	SD	F ratio	*P*
BICOR	60	96.7	5.5	47	88.8	4.6	63.43	.0000*
BICONEX	66	118.2	6.1	52	110.7	6.3	42.73	.0000*
BICONIN	66	79.6	5.4	52	76.5	4.8	10.53	.0015*
RAHR	66	64.5	5.2	50	55.2	4.2	104.67	.0000*
RAHL	65	63.5	4.6	51	54.7	4.2	113.29	.0000*
CORPLEN	65	75.8	4.5	52	71.2	3.8	34.52	.0000*
GONANG	66	124.4	8.3	51	128.6	7.2	8.39	.0045
BIGOBR	64	100.4	6.5	52	91.9	5.3	58.41	.0000*
CONHTR	66	57.3	7.1	52	47.3	6.6	62.07	.0000*
CONHTL	66	56.1	7.4	52	46.8	6.2	52.97	.0000*
CORHTR	64	63.8	5.3	49	54.9	5.3	78.68	.0000*
CORHTL	63	64.3	5.5	49	55.2	4.5	87.13	.0000*
MANLEN	66	108.5	5.5	52	101.9	4.2	51.57	.0000*
RAMBRR	65	31.1	3.1	52	28.1	2.8	30.02	.0000*
RAMBRL	65	31.0	3.0	52	28.1	2.8	27.36	.0000*
ABHTRAH	62	30.2	2.6	52	27.7	2.8	23.21	.0000*
ABHTRPH	64	26.4	2.6	52	22.5	3.4	47.34	.0000*
ABHTLAH	66	30.4	3.3	52	27.5	2.9	24.94	.0000*
ABHTLPH	66	26.2	3.4	52	22.0	3.4	45.89	.0000*
COSTRR	66	20.4	1.9	52	18.0	2.1	42.67	.0000*
COSTRL	66	20.3	1.9	52	18.3	2.1	30.66	.0000*
COSAPR	66	6.8	1.1	52	6.6	1.3	.91	.3429
COSAPL	63	6.8	1.0	52	6.7	1.4	.10	.7529
COPRAM	63	141.5	12.4	48	144.2	12.6	1.35	.2487

[1]BICOR, bicoronoid breadth; BICONEX and BICONIN, bicondylar breadth; RAH, ramus height; CORPLEN, mandibular corpus length; GONANG, gonial angle; BIGOBR, bigonial breadth; CONHT, condylar height; CORHT, coronoid height; MANLEN, mandibular length; RAMBR, ramus breadth; ABHT...H, alveolar bone height; COSTR, condylar breadth; COSAP, condylar A-P dimensions; COPRAM, condylar projected angle.
*Significance = $P < 0.002$ (using Bonferoni criterion).

breadth measurements intersect, was measured with a protractor.

Dental classification

Dentition was classified using a modified version of Granado's (1979) criteria as follows: CD—complete natural dentition, at least one molar per quadrant providing posterior support; TE—total edentulism, all teeth missing; PE—posterior edentulism, missing eight posterior teeth in one jaw; PMCD—anterior teeth present, at least one molar present in three quadrants, premolar support only in fourth quadrant (quadrant of missing molars noted—e.g., right upper, right lower, left upper, or left lower).

Although we attempted to avoid specimens categorized as PMCD or PE, due to a paucity of fully dentate female crania, seven females with PMCD and seven crania categorized as PE were included in the study.

To test the reliability of each measure, repeated measurements were taken on a subset of 20 selected skulls. No significant differences between the repeated measurements were found by the paired-comparison t-test, and the reliability coefficient was found to be high (0.99).

For each characteristic, the mean (X) and standard deviation (SD) were calculated. Differences between the sample populations in question were calculated by analysis of variance (ANOVA). Since we used a large number of measures, we applied the Bonferoni criterion to determine the level of significance. To detect the interrelationship between TMJ and craniofacial measures, we performed cluster analysis based on the average linkage method and principal-component analysis (PCA) based on the correlation matrix of all measures. The results were evaluated following orthogonal rotation of the extracted components (BMDP statistical software) [Dixon, 1988].

RESULTS

Our initial objective was to ensure that the four sample groups represented four different populations. Statistical comparison of the craniofacial skeleton of the E-A fully dentate male sample to the other three groups

TABLE 3. Craniofacial measurements, African-American vs. Euro-American, male only, complete dentition

Trait[1]	E-A Males N	Mean	SD	A-A Males N	Mean	SD	Difference F ratio	P
BIZBR	63	131.7	5.8	58	130.8	6.4	.67	.4162
FAPR	66	11.7	1.4	60	11.1	1.4	5.50	.0206
FAPL	66	11.8	1.4	60	11.6	1.3	1.00	.3191
FTRR	66	25.7	2.1	60	26.7	2.5	6.19	.0142
FTRL	66	25.6	2.2	60	26.3	2.4	2.53	.1142
FDR	65	8.9	1.2	57	9.3	1.5	2.94	.0892
FDL	66	9.0	1.3	57	9.5	1.4	4.60	.0340
FANR	63	24.5	5.2	59	25.0	6.3	.27	.6030
FANL	66	24.9	5.1	54	24.6	5.0	.10	.7487
FANPR	63	131.0	8.2	59	131.3	11.4	.02	.8820
AESRM	66	38.1	7.6	58	36.1	9.3	1.72	.1922
AESRL	64	31.4	7.6	58	33.1	7.3	1.53	.2188
AESLM	66	35.8	7.7	59	31.8	8.4	7.46	.0072
AESLL	66	29.8	7.5	59	32.6	8.2	3.95	.0492
GL	63	94.5	5.4	52	102.0	5.6	54.76	.0000*
LB	61	99.5	3.1	52	100.4	4.6	1.69	.1961
INDEX	63	94.3%	4.7%	51	101.5%	4.4%	69.54	.0000*
ZTAER	66	45.0	4.8	56	45.0	3.8	.00	.9780
ZTAEL	66	44.7	4.8	60	45.4	5.2	.59	.4427
TAER	61	49.5	3.2	60	48.0	4.4	4.72	.0318
TAEL	66	49.9	4.0	60	48.7	4.4	2.54	.1135

[1]The definitions of these acronyms are given in Table 1.
* Significance = $P < 0.002$ (using Bonferoni criterion).

(E-A fully dentate females, A-A fully dentate males, E-A edentulous males) was in accordance with our expectations. For example, E-A fully dentate males had significantly larger mean bizygomatic breadth than E-A fully dentate females, significantly smaller mean gnathic indices than A-A fully dentate males, and significantly larger mean alveolar bone heights in every position than E-A edentulous males.

Tables 1–6 show means, standard deviations, and analysis of variance results for the craniofacial and mandibular fossa measurements and compare E-A males with complete dentition with E-A females with complete dentition (Tables 1, 2), A-A males with complete dentition (Tables 3, 4), and E-A edentulous males (Tables 5, 6). Finally, it should be noted that only samples of adequate size were used to examine the effect of the following factors.

Sex factor

Euro-American fully dentate males vs. E-A fully dentate females

Fossa metrics. Significant differences in mandibular fossa breadth between males and females were found. Anteroposterior fossa dimensions, fossa depth, fossa angle, and medial and lateral articular eminence slopes were not significantly different between the male and female sample populations.

Condylar metrics. Significant differences in condylar breadth were found. Anteroposterior condylar dimensions as well as the projected condylar angle were not found to be significantly different between the male and female sample populations.

Craniofacial metrics. The gnathic index and attachments of the muscles of mastication of the female sample were significantly smaller than that of the male. All of the 21 additional mandibular measurements demonstrated highly significant differences between the sexes.

In sum, while significant differences in the craniofacial skeleton as a whole and in the insertions of the muscles of mastication specifically are known to exist between modern human males and females, in the TMJ, significant differences between the sexes were found only in the transverse dimension. The TMJ anteroposterior dimension and projected angles did not vary between the sexes, despite the large size differences which were found between male and female skulls.

Ethnic factor

Euro-American fully dentate males vs. African-American fully dentate males

Fossa metrics. No significant differ-

TABLE 4. Mandibular measurements, African-American vs. Euro-American, male only, complete dentition

	E-A			A-A			Difference	
Trait[1]	N	Mean	SD	N	Mean	SD	F ratio	*P*
BICOR	60	96.7	5.5	58	96.0	5.9	.48	.4879
BICONEX	66	118.2	6.1	57	115.9	5.9	4.60	.0340
BICONIN	66	79.6	5.4	58	77.4	5.0	5.75	.0180
RAHR	66	64.5	5.2	60	61.6	4.8	9.95	.0020*
RAHL	65	63.5	4.6	60	60.6	4.5	12.84	.0005*
CORPLEN	65	75.8	4.5	59	81.4	5.7	36.78	.0000*
GONANG	66	124.4	8.3	60	122.6	8.2	1.45	.2309
BIGOBR	64	100.4	6.5	58	98.9	8.0	1.27	.2629
CONHTR	66	57.3	7.1	60	55.9	6.0	1.37	.2445
CONHTL	66	56.1	7.4	60	54.5	6.3	1.60	.2081
CORHTR	64	63.8	5.3	57	63.1	5.9	.38	.5412
CORHTL	63	64.3	5.5	58	62.9	5.7	1.99	.1607
MANLEN	66	108.5	5.5	59	110.6	6.7	3.75	.0551
RAMBRR	65	31.1	3.0	60	33.0	3.4	11.31	.0010*
RAMBRL	65	31.0	3.0	60	33.3	3.6	15.63	.0001*
ABHTRAH	62	30.2	2.6	60	33.6	3.2	44.32	.0000*
ABHTRPH	64	26.4	2.6	60	25.7	3.0	1.87	.1740
ABHTLAH	66	30.4	3.3	60	33.7	3.4	30.59	.0000*
ABHTLPH	66	26.2	3.4	60	26.0	3.5	.18	.6706
COSTRR	66	20.4	1.9	57	20.8	1.6	1.61	.2076
COSTRL	66	20.3	1.9	59	20.5	1.8	.25	.6149
COSAPR	66	6.8	1.1	57	7.2	1.2	3.18	.0770
COSAPL	63	6.8	1.0	58	7.2	1.1	5.06	.0263
COPRAM	63	141.5	12.4	58	142.1	13.1	.07	.7879

[1] The definitions of these acronyms are given in Table 2.
* Significance = $P < 0.002$ (using Bonferoni criterion).

TABLE 5. Craniofacial measurements, edentulous vs. complete dentition, Euro-American males only

	With teeth			Edentulous			Difference	
Trait[1]	N	Mean	SD	N	Mean	SD	F ratio	*P*
BIZBR	63	131.7	5.8	46	130.7	5.5	.94	.3355
FAPR	66	11.7	1.4	50	11.1	1.2	6.54	.0119
FAPL	66	11.8	1.4	47	11.3	1.1	4.83	.0300
FTRR	66	25.7	2.1	50	26.4	1.9	3.43	.0667
FTRL	66	25.6	2.2	51	26.2	1.9	2.56	.1121
FDR	65	8.9	1.2	51	9.5	1.4	6.26	.0138
FDL	66	9.0	1.3	51	9.6	1.4	6.07	.0153
FANR	63	24.5	5.2	51	25.4	5.2	.90	.3446
FANL	66	24.9	5.1	51	23.5	5.2	2.22	.1392
FANPR	63	131.1	8.2	51	131.5	8.2	.08	.7786
AESRM	66	38.1	7.6	51	38.4	7.3	.04	.8330
AESRL	64	31.4	7.6	49	31.2	5.9	.02	.8844
AESLM	66	35.8	7.7	50	33.1	6.5	4.00	.0478
AESLL	66	29.8	7.5	51	31.2	8.4	.91	.3429
ZTAER	66	45.0	4.8	51	42.3	5.3	8.22	.0049
ZTAEL	66	44.7	4.8	51	43.9	4.3	.79	.3755
TAER	61	49.5	3.2	51	47.3	4.2	9.84	.0022*
TAEL	66	49.9	4.0	51	49.2	4.3	.70	.4045

[1] The definitions of these acronyms are given in Table 1.
* Significance = $P < 0.002$ (using Bonferoni criterion).

ences were noted between these two sample populations.

Condylar metrics. No significant differences were noted between these two sample populations.

Craniofacial metrics. The differences observed between A-A and E-A were in gnathic index, ramus height and breadth, corpus length, and alveolar bone height.

In sum, despite the large craniofacial differences between A-A and E-A, TMJ size and shape did not vary according to ethnic group. Articular eminence slope demonstrated a highly significant degree of asymmetry

TABLE 6. Mandibular measurements, edentulous vs. complete dentition, Euro-American, males only

	With teeth			Edentulous			Difference	
Trait[1]	N	Mean	SD	N	Mean	SD	F ratio	*P*
BICOR	60	96.7	5.5	45	97.4	5.1	.43	.5133
BICONEX	66	118.2	6.1	50	118.5	7.3	.06	.8057
BICONIN	66	79.6	5.4	49	80.3	4.9	.56	.4548
RAHR	66	64.5	5.2	51	60.9	5.0	14.17	.0003*
RAHL	65	63.5	4.6	51	60.0	5.3	14.67	.0002*
CORPLEN	65	75.8	4.5	51	74.5	5.3	2.10	.1497
GONANG	66	124.4	8.3	51	127.8	8.5	4.86	.0295
BIGOBR	64	100.4	6.5	50	100.5	6.4	.01	.9363
CONHTR	66	57.3	7.1	51	52.5	7.4	12.46	.0006*
CONHTL	66	56.1	7.4	51	51.3	7.5	11.58	.0009*
CORHTR	64	63.8	5.3	47	62.1	5.5	2.72	.1022
CORHTL	63	64.3	5.5	49	62.3	6.0	3.29	.0726
MANLEN	66	108.5	5.5	48	108.3	5.5	.01	.9075
RAMBRR	65	31.1	3.0	51	28.7	3.3	16.38	.0001*
RAMBRL	65	31.0	3.0	51	28.7	3.3	15.43	.0001*
ABHTRAH	62	30.2	2.6	47	25.0	3.3	83.59	.0000*
ABHTRPH	64	26.4	2.6	51	19.1	4.4	122.66	.0000*
ABHTLAH	66	30.4	3.3	45	24.8	3.2	79.72	.0000*
ABHTLPH	66	26.2	3.4	51	18.7	3.8	127.35	.0000*
COSTRR	66	20.4	1.9	51	20.8	2.3	1.04	.3094
COSTRL	66	20.3	1.9	51	20.6	2.7	.24	.6241
COSAPR	66	6.8	1.1	51	6.7	1.1	.10	.7493
COSAPL	63	6.8	1.0	47	6.7	1.1	.42	.5164
COPRAM	63	141.5	12.4	50	142.4	11.1	.16	.6892

[1] The definitions of these acronyms are given in Table 2.
* Significance = $P < 0.002$ (using Bonferoni criterion).

within all subsample populations. The right slope was consistently steeper regardless of sex or ethnic origin.

Edentulism as a factor

Euro-American fully dentate males vs. E-A edentulous males

Fossa metrics. No significant differences were noted between these two sample populations.

Condylar metrics. No significant differences were noted between these two sample populations.

Craniofacial metrics. The insertion of the temporalis and masseter muscles on the right side differed significantly between the two sample populations. Ramus height and breadth, condylar height, and alveolar bone height demonstrated significant differences.

Age factor

We divided our sample into three age groups (male only): 18–35 years, 36–49 years, 50+ years. One-way analysis of variance showed age to have no effect on any of the TMJ metric parameters (Table 7).

Principal components analysis (PCA) and cluster analysis

Analysis of variance showed that anterior-posterior TMJ dimensions are not correlated with any of the three aforementioned factors. The PCA rotated factor matrix (Table 8) shows that the TMJ measures make a relatively small contribution to the explained variance between the sample populations. The articular eminence slope measurements are highly loaded in the fourth factor and the projected condylar and fossa angles in the fifth factor; fossa A-P dimension has a high negative loading in the sixth factor along with a high positive loading for the temporalis and masseteric insertions. Fossa depth is highly loaded in the seventh factor and the condylar A-P dimension in the eighth.

Cluster analysis of all craniofacial measurements used in the present study (Fig. 2) clearly shows that the TMJ A-P measurements form separate subclusters, weakly related to the other clusters.

Relative position of mandibular fossa

According to our statistical analyses, the position of the mandibular fossa and fossa

TABLE 7. Fossa and condylar measurements according to age group: Results of one-way analysis of variance comparing Euro-American males, African-American males, and edentulous Euro-American males

	Age 20–35 years			Age 36–49 years			Age 50+ years			
Trait[1]	N	Mean	SD	N	Mean	SD	N	Mean	SD	*P*
FAP	51	11.6	1.3	49	11.3	1.4	56	11.1	1.4	.2190
FTR	52	26.4	2.6	49	26.3	2.3	56	26.5	2.1	.3921
AESM	51	38.3	9.0	47	38.8	6.7	56	37.1	7.6	.4403
AESL	51	32.5	6.7	47	31.6	7.4	54	30.1	6.4	.2472
COSAP	52	6.7	1.1	48	7.0	1.4	56	6.8	1.1	.4229
COSTR	52	20.6	2.0	49	20.6	2.0	55	20.6	2.4	.2707

[1] FAP, fossa dimensions, anterior to posterior; FTR, fossa dimensions, medial to lateral; AESM, articular eminence slope, medial aspect; AESL, articular eminence slope, lateral aspect; COSAP, anteroposterior condylar dimensions; COSTR, condylar breadth.

angle vis-à-vis the foramen magnum (B-I) did not vary with sex, ethnic origin, or edentulism. The lack of correlation between the position of the mandibular fossa (B-I) and facial dimensions (represented by mandibular corpus length) is clearly seen in Figure 3. In contrast, the distance A-I is highly correlated with facial size and shape (Fig. 4)

DISCUSSION

In this study we have shown that while craniofacial size and shape is largely affected by intrinsic and extrinsic factors, almost all architectural parameters of the TMJ, such as fossa and condylar A-P dimensions, fossa depth, condylar and fossa angles, and articular eminence slope measurements, are not.

A detailed review of the literature reveals both support and refutation of almost any claims put forth regarding the nature of TMJ morphology. For example, in a study of 200 male and 61 female crania, Demircioglu (1961) found males to possess significantly deeper fossae than females. Nevakari (1960), on the other hand, performed a radiographic study of 200 male and 200 female crania and found no difference in mandibular fossa depth.

We found no support for the notion that edentulism significantly alters the metric parameters used to describe the bony TMJ. This is in accordance with the findings of Oberg et al. (1971) and Angel (1944). Hinton (1981), on the other hand, found that increased stress on the dentition caused changes in fossa depth and articular eminence slope. Granados (1979) found that totally edentulous specimens had lower articular eminence slopes than crania with complete natural dentition. Mongini (1972) found that edentulism, not age, influenced internal condylar remodeling. Similarly, Kantomaa (1988, 1989) and Muir and Goss (1990) reported increased remodeling of the TMJ due to edentulism. Age changes, regardless of dentition, were also reported (Moffett et al., 1964; Lindblom, 1960).

The discrepancy between our results and many of the other authors may be due to the following facts. 1) Individuals in the Hamann-Todd collection were urban dwellers whose soft diets might have failed to produce significant stresses on the articular tissues. 2) The earlier studies referred to in this paper were performed on varying materials including X-rays, autopsy material, and dry skeletal material. 3) Sample size varied greatly between the studies. 4) Measurement techniques to evaluate TMJ dimensions differed greatly from study to study. 5) Statistical analyses varied between the studies. Since we used a large set of measurements, we applied the stringent Bonferoni criterion to determine the level of significance. This was not used by any of the other mentioned studies. 6) Some of the research relates to pathologic changes in bone morphology (e.g., arthrotic changes) associated with metric data; in the present study, we addressed metric parameters only. 7) It is possible that comparison of TMJ dimensions between a population whose diet is based on unprocessed food (e.g., Eskimos) and one with a diet of highly processed food (e.g., Hamann-Todd collection) would demonstrate significant differences.

An additional factor should be considered in this respect—that is, the mechanisms that control the growth and development of the eminence (which forms the anterior bor-

DISTANCE METRIC IS EUCLIDEAN DISTANCE
AVERAGE LINKAGE METHOD

TREE DIAGRAM

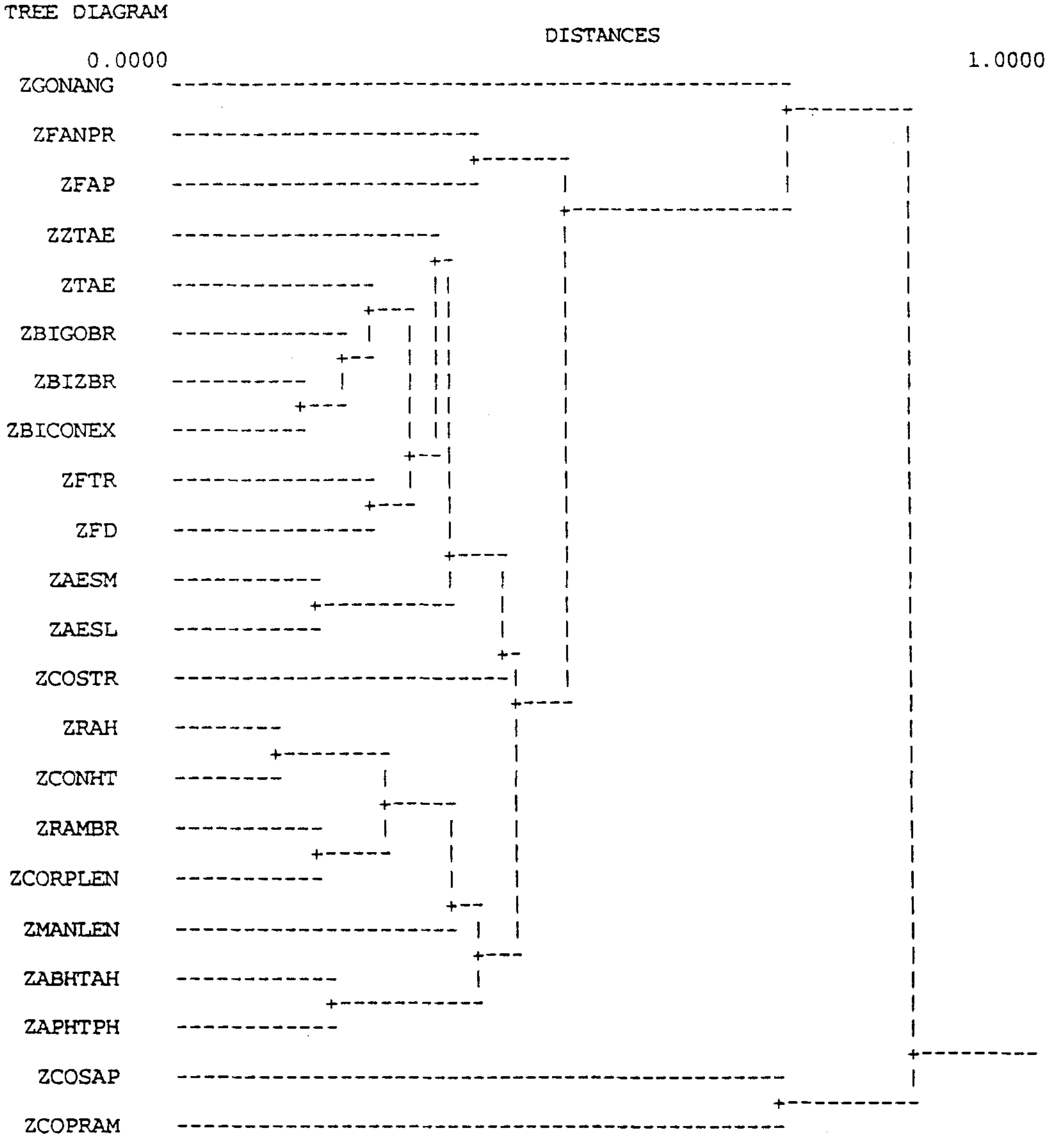

Fig. 2. Cluster analysis of the craniofacial measurements used in the present study (based on the average linkage method, Z scores). Z prefix, Z score; FTR, fossa breadth, transverse dimension; FAP, anteroposterior fossa dimension; FANPR, fossa projected angle; TAE, frontotemporale to articular tubercle; ZTAE, zygomatic tubercle to articular tubercle; AESL, lateral slope of articular eminence; AESM, medial slope of articular eminence; FD, fossa depth; COSTR, condylar breadth; COSAP, anteroposterior condylar dimension; COPRAM, projected condylar angle; GONANG, gonial angle; BIGOBR, bigonial breadth; BIZBR, bizygomatic breadth; BICONEX, bicondylar breadth, external aspect; RAH, ramus height; CONHT, condylar height; RAMBR, ramus breadth; CORPLEN, corpus length; MANLEN, mandibular length; ABHTAH, alveolar bone, anterior height; ABHTPH, alveolar bone, posterior height.

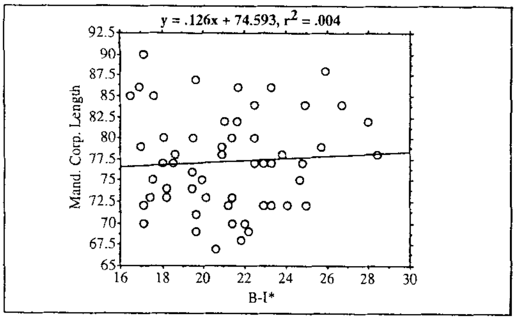

Fig. 3. Regression line expressing the relationship between the location of the TMJ on the cranial base, relative to basion, and facial size. *The distance from basion (along a mid-sagittal line drawn between alveolare and basion) to a perpendicular line connecting the most inferolateral points on bilateral articular tubercles.

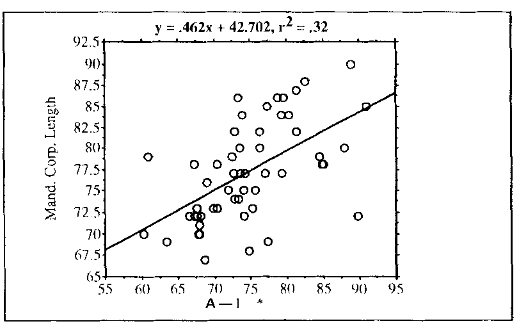

Fig. 4. Regression line expressing the relationship between the location of the TMJ on the cranial base, relative to alveolare, and facial size. *The distance from alveolare (along a midsagittal line between alveolare and basion) to a perpendicular line connecting the most inferolateral points on bilateral articular tubercles (TRART).

der of the bony TMJ) (Nickel and McLachlan, 1994). The articular eminence develops very early in life. By adolescence, significant growth no longer occurs because the "growth potential of the eminence is dependent on the mesenchymal cell population which has been rapidly depleted during the early years of growth (Nickel et al., 1988a:909). Under these circumstances, we would not expect postadolescent changes in TMJ anteroposterior dimensions.

Our results concerning TMJ anterior-posterior (A-P) dimensions are in agreement with Oberg et al. (1971) and in partial agreement with Solberg et al. (1985), who found no differences in condylar A-P dimensions between the sexes but moderately significant anteroposterior-posterior differences in fossa dimensions. The results are in disagreement with Lindblom (1960), who suggested that females generally have smaller TMJs than males.

In contrast to the conflicting results in the literature concerning the TMJ anteroposterior-posterior dimension, there is general agreement concerning the transverse dimension of the TMJ. Significant differences between males and females were noted in measurements of fossa and condylar breadth. These are consistent with the findings of Solberg et al. (1985), Hinton (1983), Wedel et al. (1978), and the trends outlined by Oberg et al. (1971).

It appears that resolution of the debate in the literature as to whether or not TMJ osseous morphology is correlated with sex, ethnic origin, or edentulism lies in altering our perception of this structure. Anthropologists customarily search for high correlations among cranial measurements. After examining a single aspect of cranial morphology, researchers often extrapolate sweeping generalizations on other aspects of cranial anatomy. These are problematic when studying the TMJ since, as shown above, its parasagittal dimensions are largely independent of its transverse dimensions. This suggests that size-related changes in the TMJ are not isometric throughout but rather demonstrate constraint in the parasagittal plane and plasticity in the transverse plane.

Our PCA and cluster analysis indicate that measurements relating to the anteroposterior dimension of the joint (i.e., condylar and fossa anteroposterior dimensions and their respective projected angles) form factors which are independent of skull size and shape (Table 8; Fig. 2). The transverse dimension, on the other hand, is closely related to other breadth measures of the skull.

This finding is not at all surprising. Phillips (1976), who looked at macaque TMJ morphometrics in relation to craniofacial parameters, claimed that joint breadth was influenced by craniofacial skeletal size, while joint anteroposterior dimensions were inde-

TABLE 8. PCA rotated factor matrix

Factors/ variable	1	2	3	4	5	6	7	8
GONANG	−.899	—	—	−.287	—	—	—	—
CONHT	.897	.281	—	—	—	—	—	—
RAH	.707	.443	—	—	—	—	—	—
RAMBR	.640	—	.472	—	—	.283	—	—
CORPLEN	.552	—	.410	—	—	—	.402	.301
BIZBR	.278	.818	—	—	—	—	—	—
BIGOBR	—	.794	—	—	—	—	—	—
BICONEX	—	.779	—	.355	—	—	—	—
FTR	—	.583	—	—	—	—	.309	—
COTR	.417	.491	—	.369	—	—	.376	—
ABHTAH	—	—	.902	—	—	—	—	—
ABHTPH	.341	—	.804	—	—	—	—	—
MANLEN	—	3464	.498	−.276	—	—	.476	—
AESL	—	—	—	.819	—	—	—	—
AESM	—	—	—	.790	—	—	—	—
COPRAM	—	—	—	—	.830	—	—	—
FANPR	—	—	—	—	.830	—	—	—
FAP	—	—	—	−.270	—	−.698	—	−.286
ZTAE	.353	—	—	—	—	.682	—	—
TAE	—	.478	—	—	—	.586	—	—
FD	—	—	—	—	—	—	.800	—
COAP	—	—	—	—	—	—	—	.850

pendent of general size parameters. Why is this so?

Before we can attempt to answer this question, another important characteristic of the TMJ which was demonstrated in our study must be noted: the relative distance between the TMJ and foramen magnum (B-I) did not vary with any of the factors in question (i.e., sex, ethnic origin, or edentulism). This is in keeping with Hoyte's (1975) reference to Brodie (1955) who looked at human basicranial growth and found that between the ages of three and eighteen "the prechordal part of the base contributed 75% of the postnatal growth in length, the parachordal (basioccipital) only 25%" (Hoyte, 1975:258).

The independent behavior (or stability) of the cranial base is a well-documented phenomenon. In 1898, Huxley claimed that "the basicranial axis is, in the ascending series of Mammalia, a relatively fixed line, on which the bones of the sides and roof of the cranial cavity, and of the face, may be said to revolve downwards and forwards or backwards, according to their position" (Huxley, 1898:195). Further, the facial skeleton and skull base have been said to "have a great degree of phylogenetic and ontogenetic independence" (Moss and Greenberg, 1955:77). Moreover, "the medial areas of the skull base are essentially stable while the lateral areas undergo prolonged change" (Moss and Greenberg, 1955:83).

In his important book on the human face, Enlow (1968:207) discussed the "disproportionate nature of growth in the calvaria and the cranial base." During growth, the expansion of the cranial vault is produced largely by drift, yet at the same time maintenance of constant relationships with the spinal cord, cranial nerves, hypophysis, auditory apparatus, etc., is provided. Furthermore, the anterior-posterior position of the foramen magnum is relatively stable in adult skulls (Enlow, 1968). Cranial nerves and major blood vessels which pass through the cranial base maintain relatively constant positional relationships with each other and with the cranial base throughout the growth period. Finally, it is not only the spatial relationships between the major anatomical structures which remain constant but also the cranial base angle that remains stable after the age of two (George, 1978).

Taking into account the above mentioned findings, we cannot escape the conclusion that there are intrinsic factors which limit the variability of the anteroposterior dimensions and the spatial position of the TMJ. The question which remains is Why this "barrier" is necessary? We hereby offer the following suggestions.

Since the size of the TMJ A-P dimension

is largely determined by the location and development of the articular eminence, it is possible that this primordially developed structure subsequently serves to set dimensional constraints. It was Kazanjian (1940) who first showed that, in the absence of mechanical loading due to condylar agenesis, the eminence will not develop. However, Nickel et al. (1988a,b), who combined evidence with theory, showed that indeed the immature joint is loaded and that this loading occurs during a period of outstanding growth of the rest of the head. In addition, early development of the eminence "might enhance the stability of the joint during the growth period of the biting apparatus" (Nickel et al., 1988a:909). All of this implies that the A-P dimensions of the TMJ develop earlier and mature earlier than do the transverse dimensions, an observation that explains the lack of isometry noted above.

It is also possible that additional factors dictate constraints on the anteroposterior dimensions of the bony TMJ. Like other components of the basicranium, the TMJ demonstrates growth patterns which are different from those of the bony face. Patterns of spatial variation which have been observed within and between some of the basicranial structures also characterize the anteroposterior dimensions of the TMJ. The position of the mandibular fossa and its A-P dimension must be independent of skull size and shape in order that a constant relationship between the major cranial-base foraminae be maintained. On the other hand, lateral growth of the mandibular fossa is possible without altering critical anatomical relationships on the basicranium. Thus, the TMJ transverse dimension is correlated with other size-related dimensions of the skull without affecting the parasagittal organization of the cranial base.

A positional relationship at the cranial base which may be of importance is that of the foramen ovale and the mandibular foramen. This relationship might be altered if the anteroposterior dimensions of the TMJ were to vary. The trigeminal nerve gives rise to the inferior alveolar nerve after it exits the cranium through the foramen ovale. The inferior alveolar nerve enters the mandible with the inferior alveolar vessels through the mandibular foramen. Since the axis of mandibular rotation is in the area of the mandibular foramen, it is possible that a change in anteroposterior TMJ dimensions might lead to changes in the position of the axis of rotation and therefore necessitate changes in the inferior alveolar nerve. Variation in the transverse dimension of the TMJ is possible without altering its axis of rotation.

Future investigation, particularly of neonate skulls, might indicate if these findings are the result of ontogenetic scaling that limits the extent of morphological diversity among adults.

In conclusion, we assert that the anteroposterior and transverse dimensions of the TMJ are subject to different sets of influences. The transverse dimension varies in accordance with size-related factors such as gender and correlates highly with other size-related cranial measurements. Anteroposterior-related dimensions, on the other hand, remain constant, as do some other cranial-base measurements. These differences in spatial constraints may in part explain the differences noted in previous studies.

The human cranial base is a highly conservative region, and we believe that the anteroposterior dimensions of the TMJ reflect this, as do the stable relations between structures such as the foramen magnum and cranial foramina.

In the light of the above, a word of caution is in order. In the present paper we have demonstrated that some aspects of the TMJ appear to have developed in correlation with the craniofacial region, while others develop independently of it. Weidenreich (1943) was probably correct in stating that some aspects of the basicranium may be influenced by the masticatory system. However, he did not seem to consider that a single anatomical structure could demonstrate behavior as two-fold as the TMJ.

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